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Per NAVSEA Task Number 88-23, the Paracel Transportable Recompression Chamber System (PTRCS) carbon dioxide (CO_2) scrubber was evaluated at the Navy Experimental Diving Unit (NEDU). The PTRCS is designed to provide emergency hyperbaric treatment capability to highly mobile, lightly supported diving activities. Unlike current U.S. Navy chambers which operate with electrically driven CO_2 scrubbers, the PTRCS CO_2 scrubber is driven using an air source outside the chamber. An amount of air equivalent to that operating the scrubber must be continuously exhausted from the chamber to maintain depth. The PTRCS CO_2 scrubber was evaluated unmanned with established NEDU procedures for canister evaluation. (These procedures define the operating characteristics of the canister, independent of the chamber containing it.) Suitable CO_2 scrubber driving pressures, CO_2 absorbent canister durations and effective air flows through the canister were determined at depths equivalent to 30, 60 and 165 feet of seawater (FSW). Prior to each canister duration test, the chamber was injected with CO_2 to a level of 1.5% (SEV).

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Next, the scrubber was operated while one standard liter per minute of CO_2 was injected into the chamber to simulate metabolic CO_2 production by a patient and tender both breathing chamber air. Canister duration was defined as the time between starting the scrubber and the point at which the rate of CO_2 elimination by the canister lagged behind the CO_2 injection rate, causing chamber CO_2 levels to rise past 1.5% SEV. At 30 FSW, adequate driving pressure was 75 psig, canister duration was 365 minutes and air consumption was 0.43 standard cubic feet per minute (SCFM). At 60 FSW, adequate driving pressure was 90 psig, canister duartion was 135 minutes, and air consumption was 0.46 SCFM. At 165 FSW, adequate driving pressure was 160 psig, canister duration was 100 minutes, and air consumption was 0.70 SCFM. To evaluate the effectiveness of the canister design for the PTRCS, an unmanned U.S. Navy Treatment Table 6A with extensions was done using the above scrubber driving pressures. CO_2 injection rate into the chamber was based on calculations of CO_2 production from human respiratory O_2 consumption studies. The chamber was pressed to 165 FSW on air, and the scrubber allowed to remove CO_2 as it was injected. This test lasted 519 minutes and used 450 standard cubic feet of air. The scrubber maintained a chamber level of less than 1.5% SEV CO_2 throughout this profile. The CO_2 absorbent canister did not require changeout.

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UNMANNED TESTING OF THE PARACEL TRANSPORTABLE RECOMPRESSION CHAMBER SYSTEM CARBON DIOXIDE SCRUBBER

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JULY 1990

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I. INTRODUCTION

Per NAVSEA Task Number 88-23, the Paracel Transportable Recompression Chamber System (PTRCS) (International Innovations Inc.-Australia) carbon dioxide (CO_2) scrubber was evaluated at the NEDU Testing and Evaluation Laboratory. The PTRCS is designed to provide emergency hyperbaric treatment capability to highly mobile, lightly supported diving activities.

The PTRCS consists of an Emergency Evacuation Chamber (EEC) and a detachable Personnel Transfer Chamber (PTC) (Figures 1 and 2). Hyperbaric treatments are conducted in the EEC. During treatment or transport in the EEC, the patient is supine on the stretcher and the tender is seated alongside to perform necessary medical assistance. The EEC is equipped with an air and oxygen Built-In Breathing Supply (BIBS), an Overboard Dump System (ODS), and a CO_2 scrubber. The compact design of the EEC allows it to fit inside a helicopter for transport under pressure. The PTC serves as an outer lock to exchange tenders and equipment when mated to the EEC.

The CO_2 scrubber is operated solely from a compressed air source outside the chamber, and needs no external power supply. Unlike electrically driven scrubbers found in conventional U.S. Navy chambers, compressed air passes through the scrubber's air ejector, drawing chamber atmosphere through the scrubber canister. As the outside compressed air source enters into the air ejector, running the scrubber, an equal amount of gas must be exhausted to maintain pressure and depth. Chamber CO_2 is removed by: (1) chemical reaction with the scrubber absorbent and, (2) in the chamber exhaust.

Per design the PTRCS scrubber supports safe levels of chamber CO_2 during hyperbaric treatments at depths of 60 FSW. For U.S. Navy uses, the scrubber must maintain safe chamber CO_2 levels with treatments involving depths of 165 FSW (Treatment Table 6A).

The PTRCS CO_2 scrubber was initially tested using protocols developed for electrically driven scrubbers (1,2). This defined the operating properties of the scrubber design independent of the chamber. For chamber pressures equivalent to depths of 30, 60, and 165 FSW, the tests identify: (a) the most suitable air supply pressures to operate the scrubber successfully; (b) the rate of gas flow through the canister at the most suitable air supply pressures; (c) the duration of time before failure of the CO_2 absorbent; (d) the rate of compressed air usage while running the scrubber at the most suitable air supply pressures.

Next, the scrubber canister of the PTRCS system was tested under expected operating conditions. A canister duration test was modeled based on the estimated CO_2 produced by one patient and one tender. This would test a single canister's ability to perform adequately during a Treatment Table 6A with two extensions at both 30 and 60 FSW (519 minutes total).

II. METHODS

Two sampling tubes (Tygon (1/8-inch I.D.)) were fed into the chamber, measuring CO_2 levels. The first tube, for chamber CO_2 measurement, was located near the chamber door in the expected area of the patient's and tender's heads. Chamber CO_2 was measured with two infrared CO_2 analyzers (Analox, Model: 0055S and Beckman, Model: 865). The second tube, to measure scrubber effluent CO_2 level, was placed at the scrubber outlet. This tube was attached to a Beckman CO_2 analyzer (Model: 880). The analyzers were calibrated daily.

The CO_2 injection rate was maintained at one standard liter per minute (SLPM) for all test runs. This rate, used in earlier scrubber studies, was intended to correspond to the total CO_2 production rate from two chamber occupants doing light work. A mass flow controller (Matheson, Model: 8200) was used to govern the injection rate of CO_2. This injection rate was verified prior to testing using a Tissot spirometer. CO_2 was injected below the presumed location of the patient's head near the chamber door. A fan was used to ensure a well-mixed chamber atmosphere, but is not intended to be present when two occupants are inside the chamber. To estimate air usage, the Tissot spirometer also collected chamber exhaust gas at various depths and supply pressures during testing.

Calibrated wet and dry digital temperature thermistors (Cole-Parmer Company (Chicago, Illinois)) were placed in the chamber and used to calculate changing humidity. Heat and moisture were not added to chamber atmosphere to simulate the amount produced by the chamber occupants. Ambient temperature in the testing facility was approximately 70°F. The chamber humidity went rapidly to 100% during each run. The largest temperature increase observed was 4°F during a six hour canister duration test.

The cylindrical scrubber canister was firmly packed with fresh High Performance Sodasorb (W.R. Grace and Company) prior to each run.

A. IDENTIFICATION OF SUITABLE AIR SUPPLY PRESSURES TO THE SCRUBBER

Air supply pressure to the scrubber should circulate the chamber atmosphere through the canister bed, maintaining safe chamber CO_2 levels. Accordingly, chamber CO_2 levels at depths of 30, 60, and 165 FSW as a function of supply pressure to the scrubber's air flow ejector were measured. The chamber was first pressed to test depth on air, then air flow to the air ejector and carbon dioxide injection were started. Once at depth, the injection rate of one SLPM of CO_2 and the selected air pressure to the scrubber air ejector were started. Chamber CO_2 concentration was recorded every 5 minutes. When the concentration of CO_2, as shown by the Analox CO_2 monitor, remained constant for a 15-minute period, chamber CO_2 was considered to have reached a steady state level and the test was terminated. The supply pressure resulting in a chamber steady state CO_2 level most closely approaching, but not exceeding 1.5% CO_2 surface equivalent value (SEV) would be the most suitable operating supply pressure for that depth. The currently accepted exposure limit of 1.5% CO_2 SEV for U.S. Navy chambers identifies when absorbent canister must be changed (3).

B. CANISTER AIR FLOW RATE DETERMINATION

Theoretically, canister bed air flow rate is a function of ejector supply pressure and chamber depth. To verify this, the chamber was pressed to depth on air and CO_2 injected with the scrubber off until the chamber level reached 1.5% SEV CO_2. CO_2 addition was stopped, the scrubber started, and chamber CO_2 concentration recorded every two minutes until readings were 0% SEV for fifteen minutes. The rate of change of chamber CO_2 was then used to calculate canister air flow rate. For both 30 and 60 FSW ejector supply pressures of 90, 105, and 120 psi were tested. For 165 FSW pressures of 150 and 160 psi were tested.

C. CANISTER DURATION BREAKTHROUGH RUNS

The canister duration test assesses the ability of the scrubber to maintain chamber CO_2 levels below a baseline level of 1.5% SEV CO_2 in the face of a constant injection of 1.0 SLPM CO_2 injection. The test procedure used in previous scrubber evaluations at NEDU (1,2) was followed. The chamber was first pressed to 4 FSW to achieve chamber seal. Carbon dioxide was then injected until the chamber CO_2 concentration at 4 FSW corresponded to 1.5% SEV for specific test depths. CO_2 injection was stopped and the chamber pressed from 4 FSW to depth (30, 60, or 165 FSW). At depth, the scrubber was started and CO_2 injection resumed at 1.0 SLPM. Chamber and canister effluent CO_2 concentrations were recorded until the chamber level exceeded 1.5% SEV. At this point canister breakthrough was defined. Supply pressures to the scrubber chosen were 75 and 90 psi at 30 FSW; 90, 105, and 120 psi at 60 FSW; and 150 and 160 psi at 165 FSW. These were the ejector supply pressures, excluding the lowest setting, which maintained steady state chamber CO_2 levels below 1.5% SEV during earlier tests.

D. COMPRESSED AIR CONSUMPTION RATES

The quantity of air expended to operate the scrubber during canister duration testing was recorded. By design the chamber must exhaust the same amount of gas as is introduced to drive the scrubber, maintaining a constant depth. Collection and measurement of this exhausted gas determined the rate of air consumption at the selected depths and pressure settings.

E. TREATMENT TABLE 6A MODEL RUN

Once the operating characteristics of the scrubber were identified, its effectiveness as a Paracel system component was studied. An unmanned U.S. Navy Treatment Table 6A with two extensions at both 60 and 30 FSW using a lower, revised CO_2 injection rate was conducted. This lower rate was calculated based on widely-accepted NASA physiologic standards for oxygen consumption at various states of human activity (4). A respiratory quotient of 0.8 for light activity was used for oxygen consumption rate to convert into carbon dioxide production rates. Accordingly, CO_2 production rates of 0.21 SLPM for the patient and 0.48 SLPM CO_2 for the tender were established for the air breathing phase. To accomplish this, a combined injection of 0.7 SLPM was used for 35 minutes at 165 FSW. This injection rate was continued for travel to 60 FSW. For the remainder of the table, the tender spends 489 minutes on air and the patient 124 minutes. Proportionally, between the patient and tender, this averaged to an injection rate of 0.53 SLPM of CO_2, from 60 FSW to the surface.

During an actual treatment, the patient should remain constantly on BIBS, while the tender goes on BIBS only when breathing oxygen. For an additional margin of safety, the patient's CO_2 production while on air was included in the injection rate, covering the possibility that the patient might remove the BIBS mask when off oxygen.

The chamber was pressed to 165 FSW on air free of initial buildup of CO_2. Using the CO_2 injection rates given above, chamber and canister effluent CO_2 levels were simultaneously measured during the table simulation. A total volume of 281.5 standard liters of CO_2 was introduced during the 519-minute treatment. Air supply pressures for 165, 60, and 30 FSW were 150, 90, and 75 psi respectively. Pressure was lowered from 90 to 75 psi during ascent to 30 FSW and was set at an average value of 60 psi for the final 30 minutes of the table (ascent to the surface).

III. TEST RESULTS

A. IDENTIFICATION OF SUITABLE AIR SUPPLY PRESSURES TO THE SCRUBBER

The optimum air supply pressure for the scrubber at depth should maintain steady state CO_2 levels just below the 1.5% SEV CO_2 value. Percent CO_2 SEV as a function of time, supply air pressure, and test depth is plotted in Figures 4-6. Table 1 reports the steady state CO_2 value for each of the selected supply pressures at the three test depths. Steady state testing data indicates that 150 psi at 165 FSW, 75 psi at 60 FSW, and 60 psi at 30 FSW were the lowest air pressure settings tested to meet this criteria.

B. CANISTER AIR FLOW RATE DETERMINATION

The rate at which an electrically driven scrubber pulls air through the absorbent can be estimated using a calculation developed during previous scrubber tests conducted at NEDU (1,2). In a closed, well-mixed chamber into which no CO_2 is being introduced after the initial chamber CO_2 level is established, and in which the canister effluent is constant, the partial pressure of chamber carbon dioxide at a given time is given by equation 1, below (2):

$$P_{CO_2} = PE_{CO_2} - (PE_{CO_2} - PS_{CO_2}) * e^{(-kt)} \qquad \text{Equation 1}$$

where:
P_{CO_2} = partial pressure of CO_2 in chamber, mmHg
PE_{CO_2} = partial pressure of CO_2 in canister effluent, mmHg
PS_{CO_2} = initial partial pressure of CO_2, mmHg
$k = \dot{V}_F/V_{CH}$
V_F = scrubber ventilation rate, actual liters/minute
V_{CH} = chamber floodable volume, liters
t = time, minutes

Rearranging and taking the natural log results in equation 2:

$$\ln(P_{CO_2} - PE_{CO_2}) = (-kt)\ln(PS_{CO_2} - PE_{CO_2}) \qquad \text{Equation 2}$$

The partial pressure of CO_2 in the scrubber effluent rapidly drops to zero. The decrease of chamber CO_2 versus time is shown in Figures 7a, 8a, and 9a. When $\ln(P_{CO_2})$ was plotted versus time a straight line was obtained (Figures 7b, 8b, and 9b). The slope of the natural log plot (-k) of the chamber partial pressure of CO_2 (P_{CO_2}) versus time will equal the ratio of canister flow to chamber volume ($\dot{V}_F/V_{CH}$). From this value, given the volume of the chamber (44 cubic feet), the scrubber canister flow rate can be determined. These values are shown in Table 2.

Canister flow test results can also be used to assess the efficiency of the scrubber air ejector. Ejector efficiency is defined as the ratio of the secondary air flow (canister flow) to the primary air flow (gas supplied to the air ejector). Both of these flows were measured during testing. Maximizing the ratio of the two flows should result in maximized ejector efficiency. Table 3 shows the calculated efficiencies for the EEC scrubber based at the various depths and supply pressures tested. Note that the efficiencies did not change with increasing supply pressures to the scrubber for each of the three depths tested. A previous study of a semi-closed Underwater Breathing Apparatus CO_2 scrubber with an air ejector has also shown that changing the air supply pressure has little effect on ejector efficiency values (5).

C. CANISTER DURATION BREAKTHROUGH RUNS

Chamber and scrubber effluent CO_2 levels as a function of time are graphically represented in Figures 10-12. Table 4 compares the steady state CO_2 values obtained earlier in the study to the lowest level of CO_2 attained by the scrubber during the canister duration test. Table 4 shows that the scrubber removes enough CO_2 to drop the chamber level close to the steady state value demonstrated at that depth and pressure setting.

Table 4 also summarizes the effect of increasing supply pressure on canister duration. At 30 FSW, canister duration increased slightly with increased supply pressure. At 60 FSW, duration was longer for 105 psi supply pressure than for 90 psi, but decreased at 120 psi. A longer canister duration was observed at 165 FSW for 150 psi than 160 psi due to the use of a slightly lower CO_2 injection rate (0.93 SLPM) at 150 psi.

D. COMPRESSED AIR CONSUMPTION RATES

The results of the exhausted air measured by the Tissot spirometer, to estimate the air introduced into the chamber to run the scrubber, are summarized in Table 5. At 30 FSW and 75 psi, air consumption was 0.43 SCFM. At 60 FSW and 90 psi, air consumption was 0.46 SCFM. At 165 FSW and 160 psi, air consumption was 0.70 SCFM.

E. TREATMENT TABLE 6A MODEL RUN

Table 6 details the rate of CO_2 injection with depth and the maximum CO_2 measured during a simulated Treatment Table 6A with extensions. Chamber CO_2 concentration for the extended Treatment Table 6A versus time is shown in Figure 13. Superimposed on this figure are depth (FSW) and CO_2 injection rates (SLPM) for this treatment profile. The highest level reached during this run was 0.85% SEV CO_2 at the end of the 165 FSW portion of the table. This is well below the 1.5% SEV CO_2 limit.

Predicted air use for the Treatment Table 6A with extensions is shown in Table 7, based on the settings used for the model run and the exhaust rates measured earlier by the Tissot spirometer. Total air consumption for the model treatment profile was 450 standard cubic feet (11,843 liters).

IV. DISCUSSION

A. IDENTIFICATION OF SUITABLE AIR SUPPLY PRESSURES TO THE SCRUBBER

Results demonstrate that the chamber steady state CO_2 concentrations decreased with increasing air pressure to the scrubber (Table 1, Figures 2, 3, and 4). Prior to breakthrough, the unit removes a portion of the injected CO_2 based on the rate at which chamber air circulates through the canister. A low supply pressure will economize air usage and increase the amount of contact or residence time between the CO_2 molecules and the absorbent material. The disadvantage of low supply pressures are that they do not circulate the chamber air through the canister as rapidly as higher supply pressures, resulting in higher chamber CO_2 levels.

The tests performed were intended to determine steady state CO_2 levels at each test depth for various scrubber air pressures, identifying the lowest supply pressure which did not exceed 1.5% CO_2 SEV. For the supply pressure settings tested in this study; 60 psi at 30 FSW, 75 psi at 60 FSW and 150 psi at 165 FSW best satisfied this requirement.

In order to determine the optimum supply pressure settings for the least amount of air consumption, further testing to determine an air pressure setting which produces exactly 1.5% SEV CO_2 at 30, 60, and 165 FSW on multiple runs is warranted. The supply pressures for the three depths given above allow for safe operation of the scrubber with economy of air use.

At the start of steady state testing, it was discovered that the absorbent scrubber canister was not sealing properly due to irregularities in the O-ring seat of the scrubber jacket (Figure 14). A seal could only be obtained by taping the outside of the canister. This design irregularity has been reported to the manufacturer and will be rectified in future models.

B. CANISTER AIR FLOW RATE DETERMINATION

Canister air flow rate studies previously done at NEDU involved closed chamber air systems, excluding air exchanged during chamber ventilations. The EEC must constantly exhaust a portion of the chamber atmosphere, a percentage of which is CO_2, during scrubber operation to maintain a constant depth. The test and equations used in earlier studies for measuring canister flow were intended for use with closed, well-mixed systems. The Paracel represents the first semi-closed system NEDU has evaluated. While this method accurately models the expected trends in the EEC scrubber ventilation rate as a function of depth and scrubber air supply pressure, part of the CO_2 being removed is actually being lost in chamber exhaust, rather than reacted with the absorbent. Hence, the ventilation values obtained are of questionable accuracy.

Calculations of air ejector efficiencies confirm that the lowest air pressure setting which produces adequate scrubbing for safe limits of CO_2 should be utilized. Higher efficiency was not attained for the greater amounts of air used with supply pressures higher than those capable of maintaining safe levels of CO_2, and air use was increased at the higher settings.

C. CANISTER DURATION BREAKTHROUGH RUNS

In theory, the scrubber absorbent should remove CO_2 from the chamber atmosphere while approaching a steady state value for a given depth and ejector supply pressure. For most of the runs the lowest level of CO_2 approximated the steady state values determined earlier in the study. However, during a breakthrough test at 60 FSW and 90 psi, 1.46% SEV CO_2 was the lowest concentration achieved throughout the run, although the steady state level established in an earlier test was 1.35% SEV CO_2. As one would expect, this indicates that the scrubber has definite limitations on the amount of CO_2 it removes from a chamber and is dependent on initial CO_2 levels and injection rates.

During actual operation, the chamber would be pressed on air with a low CO_2 initial concentration (0.18 % at 6ATA max). If the scrubber can maintain a low CO_2 level at this depth, the 60 FSW portion of a treatment will also begin in a low CO_2 atmosphere (Figure 11).

D. COMPRESSED AIR CONSUMPTION RATES

Canister air flow calculations from prior studies of closed chamber systems assume no loss of CO_2 from the chamber during operation. While the PTRCS continually exhausts a portion of the chamber atmosphere to maintain depth, the calculated values of PTRCS canister air flow do show trends similar to those of closed chamber systems. For a constant air supply pressure, air flow through the canister bed decreased with depth, and at depth increasing the air supply pressure increased canister bed flow. Accordingly, to optimize actual air use at depth, air supply pressures should be used as follows: 0.43 SCFM at 30 FSW and 75 psi, 0.46 SCFM at 60 FSW and 90 psi, and 0.70 SCFM at 165 FSW and 160 psi.

E. TREATMENT TABLE 6A MODEL RUN

The results of the model Treatment Table 6A test were positive. Using a CO_2 injection profile based on physiologic modeling of human CO_2 production and pressing the chamber on ambient air allowed the canister to easily maintain levels below 0.85% SEV for the entire profile. Even with extensions, one canister can successfully support treatment.

V. SUMMARY

Following established NEDU test procedures, the operating characteristics of the PTRCS CO_2 scrubber was first studied. Suitable scrubber supply pressures, CO_2 absorbent canister durations, and scrubber operation air consumption rates were determined for 30, 60, and 165 FSW. At 30 FSW, suitable air supply pressure was 75 psig, canister duration was 365 minutes, and air consumption was 0.43 SCFM. At 60 FSW, suitable air supply pressure was 90 psig, canister duration was 135 minutes, and air consumption was 0.46 SCFM. At 165 FSW, suitable air supply pressure was 160 psig, canister duration was 100 minutes, and air consumption was 0.70 SCFM.

To study the effectiveness of the semi-closed scrubber design for the PTRCS chamber, an unmanned dive profile simulating a U.S. Navy Treatment Table 6A with two extensions at both 60 and 30 FSW was done. The CO_2 production rate for a patient and tender was lowered from 1.0 SLPM, used in earlier NEDU studies, to 0.7 SLPM at 165 FSW and 0.53 SLPM at 60 and 30 FSW, based on NASA human respiratory physiology measurements (4). The chamber was pressed to depth on air (low ambient CO_2 levels), and CO_2 injection was then begun. This test lasted 519 minutes and consumed 450 standard cubic feet of air. The scrubber was able to maintain a safe CO_2 level in the chamber (less than 0.85% SEV CO_2) throughout this profile with no need for changing the CO_2 absorbent canister.

Unmanned testing of the carbon dioxide removal system of the Emergency Evacuation Chamber indicates that the scrubber, in its current configuration, is capable of maintaining an acceptably low level of CO_2 (less than 1.5% SEV) for long treatments.

Chamber CO_2 levels can be monitored by the inside occupants with chemical detection tubes which are rugged and reliable. This should be conducted in accordance with Volume I of the U.S. Navy Dive Manual (3).

A design modification is suggested to change the ratio of the area of the venturi opening to the area of the scrubber pipe using a No. 75 (0.021 inch) drill bit. A previous study (5) has found that optimizing this ratio results in increased scrubber jet pump efficiency.

Should the scrubber design for the PTRCS change in the future, further testing will be required. These tests should focus on the identification of air supply pressures which keep chamber CO_2 just below 1.5% CO_2 to meet current specifications for U.S. Navy chambers.

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TABLE 1

STEADY STATE CHAMBER CO_2 LEVELS AS A FUNCTION OF DEPTH AND SCRUBBER SUPPLY PRESSURE

Test Depth (fsw)	Supply Pressure (psi)	Chamber % CO_2 at Steady State (SEV)
30	60	1.36
"	75	1.19
"	90	1.05
"	105	0.91
"	120	0.81
"	140	0.72
60	75	1.42
"	90	1.35
"	105	1.12
"	120	0.95
"	140	0.85
165	140	1.73
"	150	1.42
"	160	1.41
"	175	1.24
"	190	1.23

TABLE 2

CANISTER AIR FLOW RATE AS A FUNCTION OF DEPTH AND SCRUBBER SUPPLY PRESSURE

Test Depth (fsw)	Scrubber Supply Pressure (psi)	Canister Air Flow Rate Actual l/m
30	90	109.6
"	105	118.9
"	120	158.4
60	90	83.6
"	105	84.3
"	120	99.8
165	150	94.5
"	160	102.2

TABLE 3

EJECTOR EFFICIENCY
AS A FUNCTION OF
DEPTH AND SCRUBBER SUPPLY PRESSURE

Test Depth (FSW)	Supply Pressure (psi)	*Primary Flow (SLPM)	**Secondary Flow (SLPM)	Ejector Efficiency (Secondary/Primary)
30	90	12.62	191.61	15.18
"	105	14.18	207.86	14.66
"	120	15.66	276.92	17.68
60	90	13.79	215.75	15.65
"	105	15.47	217.55	14.06
"	120	17.55	257.56	14.67
165	150	16.15	515.14	31.89
	160	18.32	557.12	30.41

* Primary flow is supply air flow to the scrubber ejector.
** Secondary air flow is canister air flow (outlet).

TABLE 4

CHAMBER CARBON DIOXIDE CONCENTRATION AND CANISTER DURATION AS A FUNCTION OF DEPTH AND SUPPLY PRESSURE DURING CANISTER DURATION TESTING

Test Depth (FSW)	Scrubber Supply Pressure (psi)	Initial Chamber % CO_2 (SEV)	Lowest % CO_2 During Test (SEV)	Canister Duration (minutes)
30	75	1.52	1.18	365
"	90	1.52	1.00	380
60	90	1.50	1.46	135
"	105	1.50	1.12	340
"	120	1.50	1.05	320
165	150*	1.66	1.43	255
"	160	1.50	1.48	100

* Inadvertent 0.93 SLPM CO_2 Injection Rate
(All Other CO_2 Injection Rates 1.0 SLPM)

TABLE 5

RATE OF AIR CONSUMPTION TO DRIVE SCRUBBER
AS A FUNCTION OF
DEPTH AND SCRUBBER SUPPLY PRESSURE

Test Depth (fsw)	Scrubber Pressure (psi)	Air Consumption Rate ** (SLPM) *	Air Consumption Rate ** (SCFM)**
30	60	9.28	0.35
"	75	11.34	0.43
"	90	12.62	0.48
"	105	14.18	0.54
"	120	15.66	0.60
60	75	9.47	0.36
"	90	12.01	0.46
"	105	13.79	0.52
"	120	15.47	0.59
"	140	17.55	0.67
165	150	16.15	0.61
"	160	18.32	0.70
"	175	20.71	0.79
"	190	22.79	0.87

* Liter per minute standardized to 0^{o} C.

** Cubic foot per minute standardized to 60^{o} F.

TABLE 6

MAXIMUM CHAMBER CO_2 LEVELS DURING A SIMULATED TREATMENT TABLE 6A WITH EXTENSIONS*
AS A FUNCTION OF
DEPTH, SCRUBBER SUPPLY PRESSURE AND RATE OF CO_2 INJECTION

Test Depth (fsw)	Scrubber Pressure (psi)	Time (minutes)	Rate of CO_2 Injection (SLPM)	Maximum $\%CO_2$ Measured (SEV)
165	150	30	0.70	0.852
165-60	150	4	0.70	0.637
60	90	125	0.53	0.654
60-30	90-75	30	0.53	0.647
30	75	300	0.53	0.634
30-0	60	30	0.53	0.756

* Denotes two extensions at both 60 FSW (25 minutes each extension) and 30 FSW (75 minutes each extension).

TABLE 7

PROJECTED AIR USE FOR A TREATMENT TABLE 6A WITH EXTENSIONS*
USING A SELECTED SCRUBBER SUPPLY PRESSURE FOR EACH DEPTH

Depth (fsw)	Time (minutes)	Supply Pressure (psi)	Air Consumption Rate (SLPM)	Air Volume Consumed std. l	Air Volume Consumed std.cu.feet
0-165		0	0	5901.9	224.50
165	30	150	16.15	484.5	18.42
165-60	4	150	16.15 **	64.6	2.46
60	125	90	12.01	1501.3	57.08
60-30	30	90 - 75	11.68 **	350.3	13.32
30	300	75	11.34	3402.0	129.35
30-0	30	60	4.64 **	139.2	5.29
			Total	11843.8	450.42

* Denotes two extensions at both 60 FSW (25 minutes each extension) and 30 FSW (75 minutes each extension).

** Average of high and low measurements for both depths.

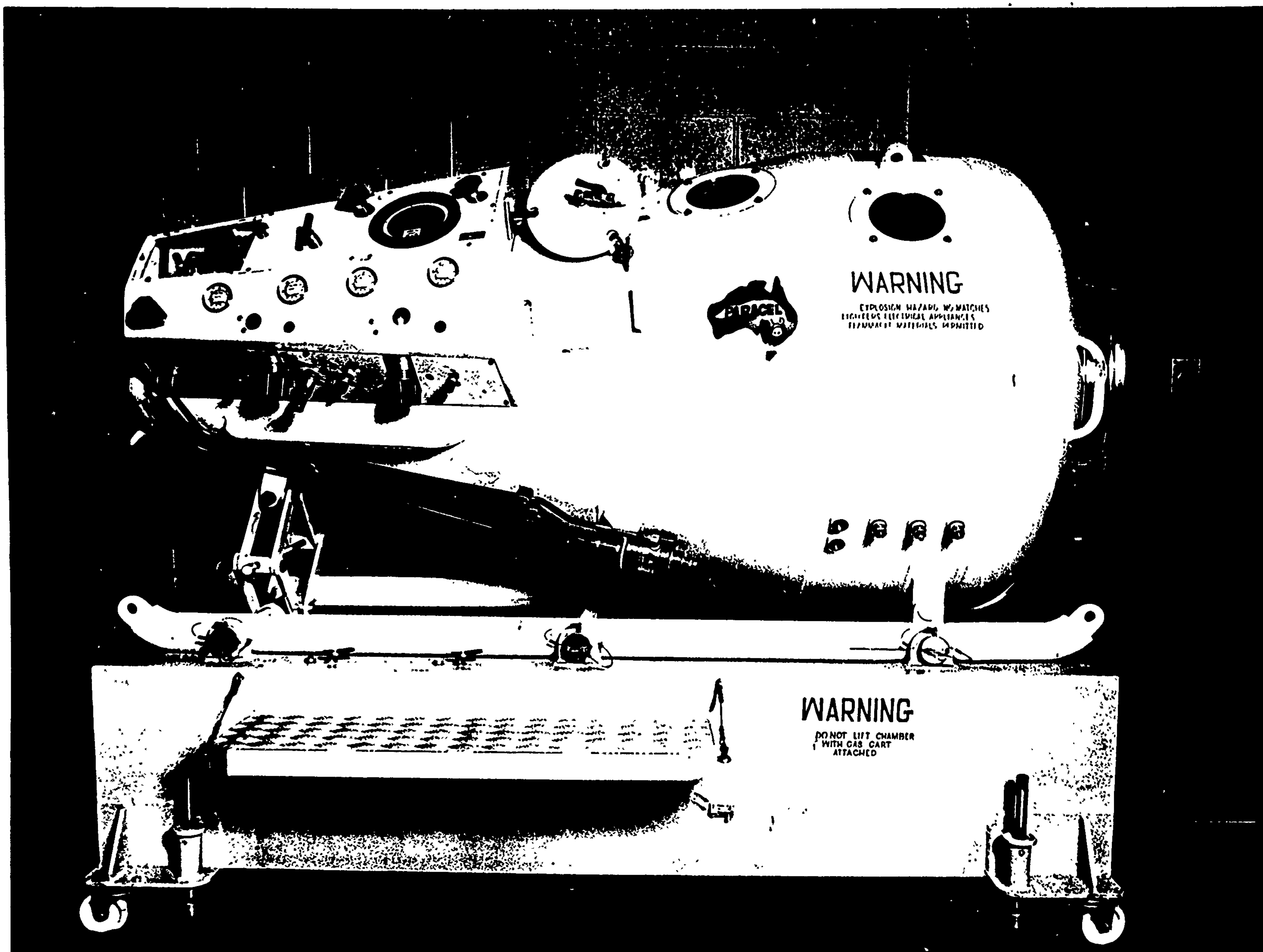


FIGURE 1. PTRCS Emergency Evacuation Chamber

PTRCS CARBON DIOXIDE CONCENTRATION

30 FSW, VARIOUS SUPPLY PRESSURES

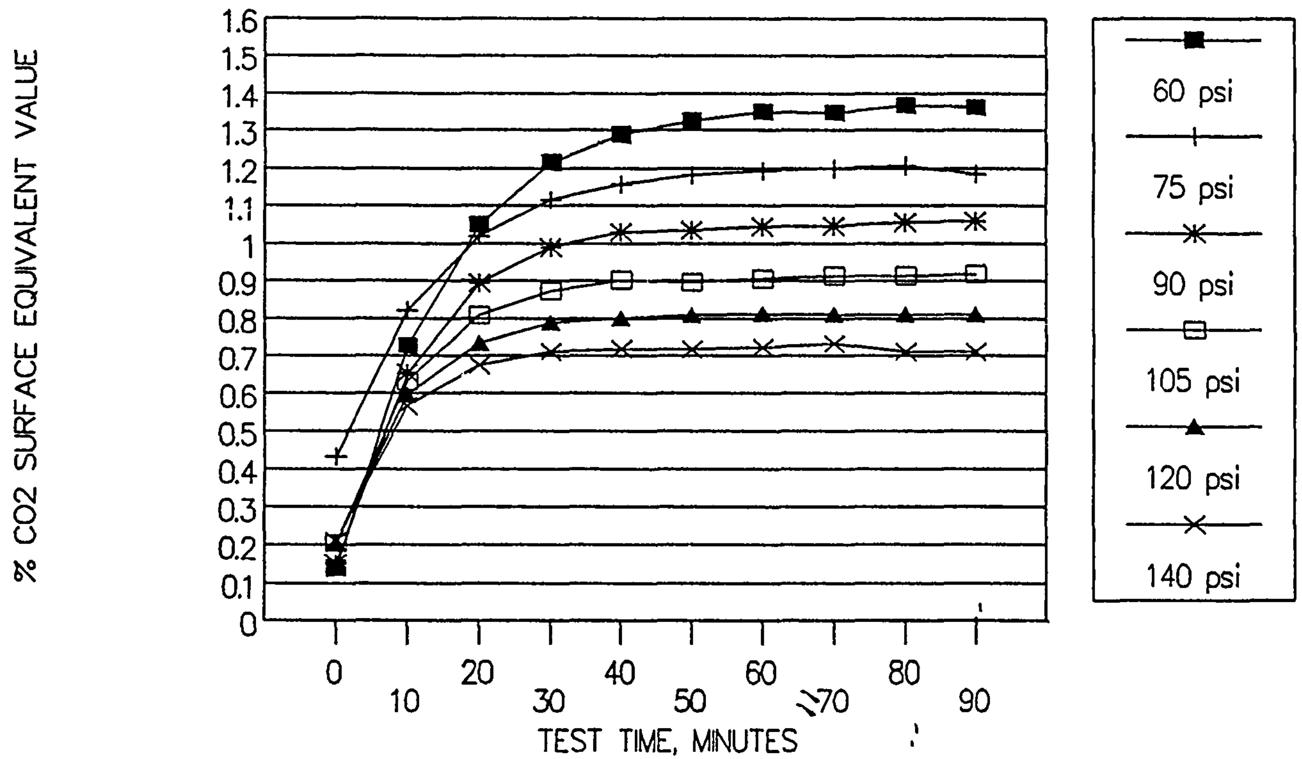


FIGURE 2

PTRCS CARBON DIOXIDE CONCENTRATION

60 FSW, VARIOUS SUPPLY PRESSURES

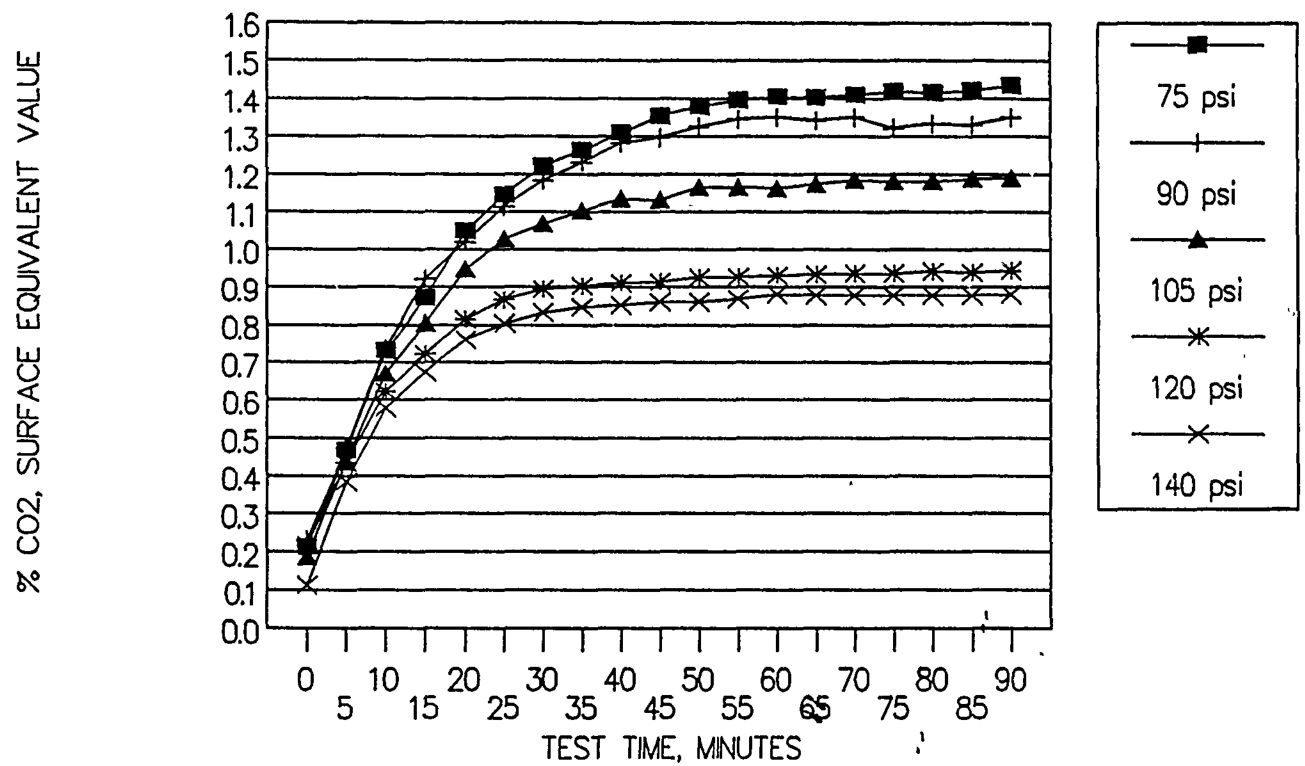


FIGURE 3

PTRCS CARBON DIOXIDE CONCENTRATION

165 FSW, VARIOUS SUPPLY PRESSURES

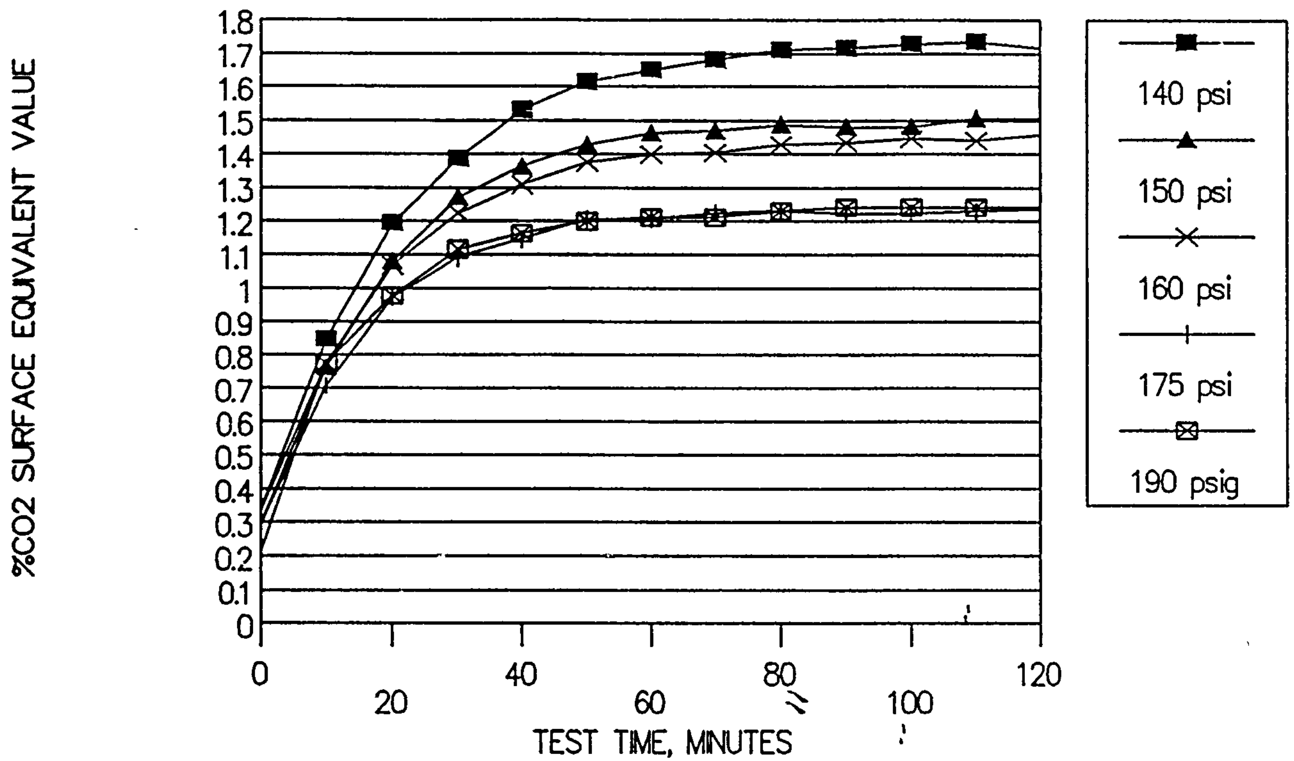


FIGURE 4

SCRUBBER FLOW STUDY - 30 FSW

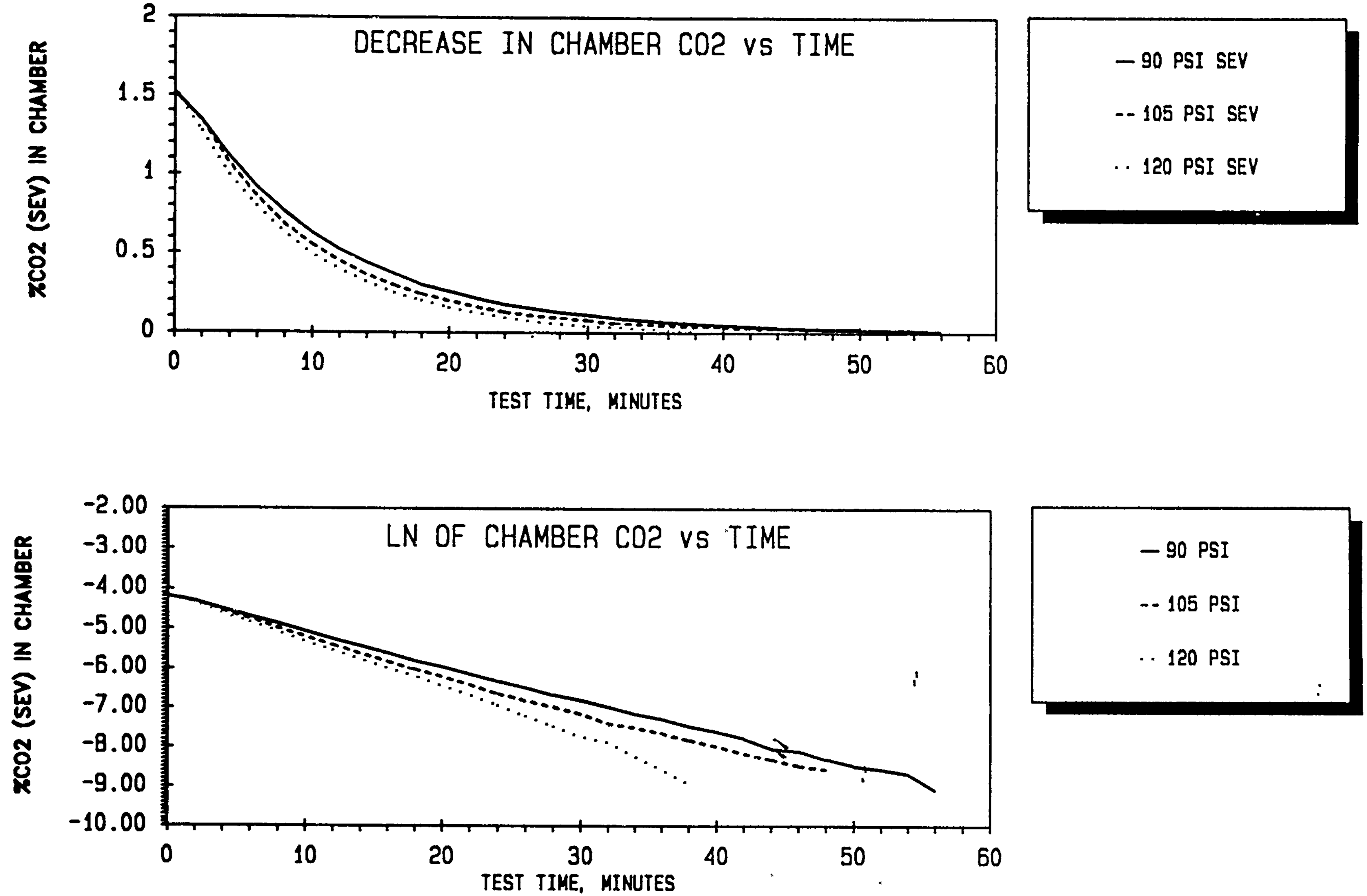


FIGURE 5

SCRUBBER FLOW STUDY - 60 FSW

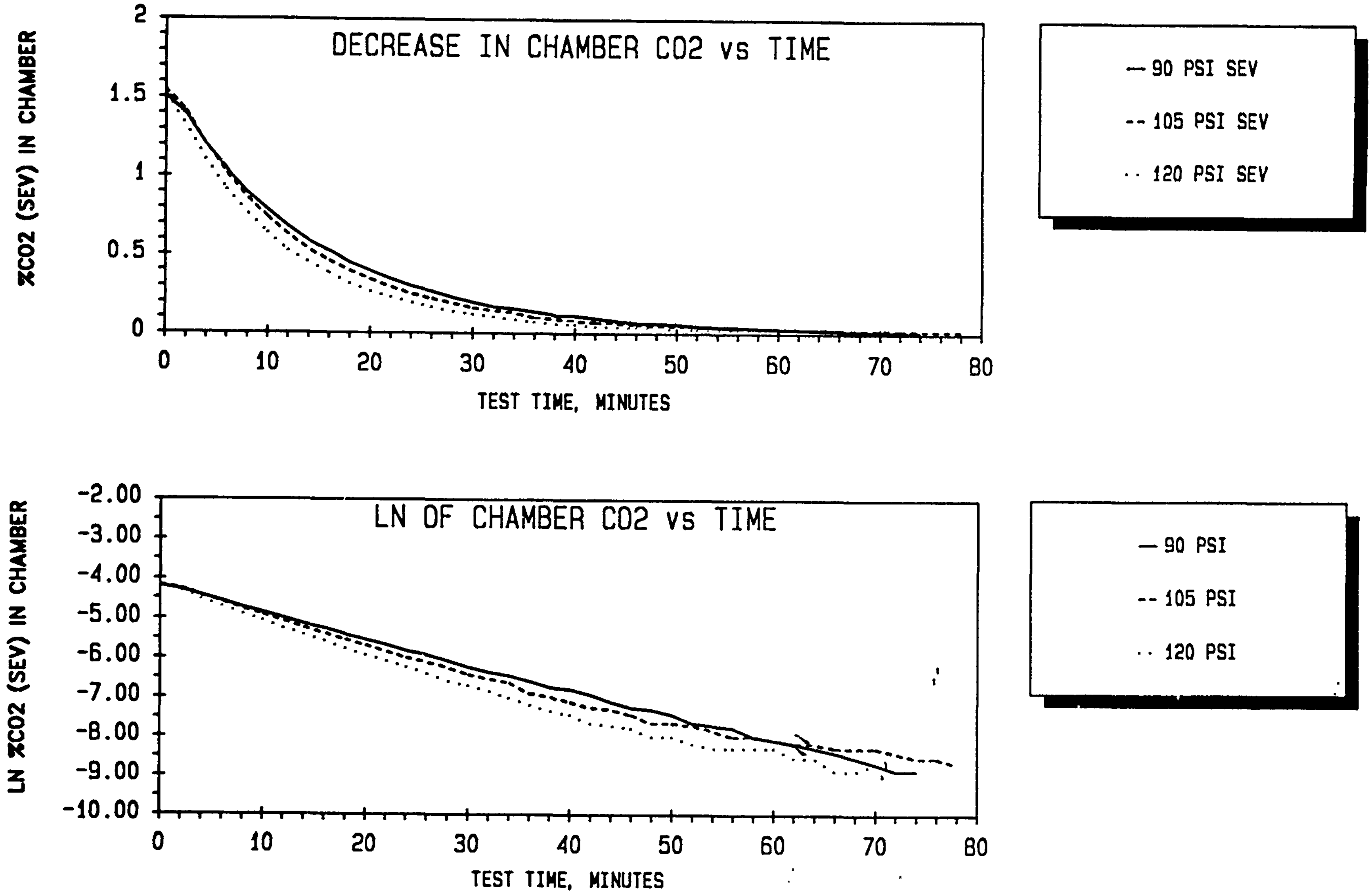


FIGURE 6

SCRUBBER FLOW STUDY - 165 FSW

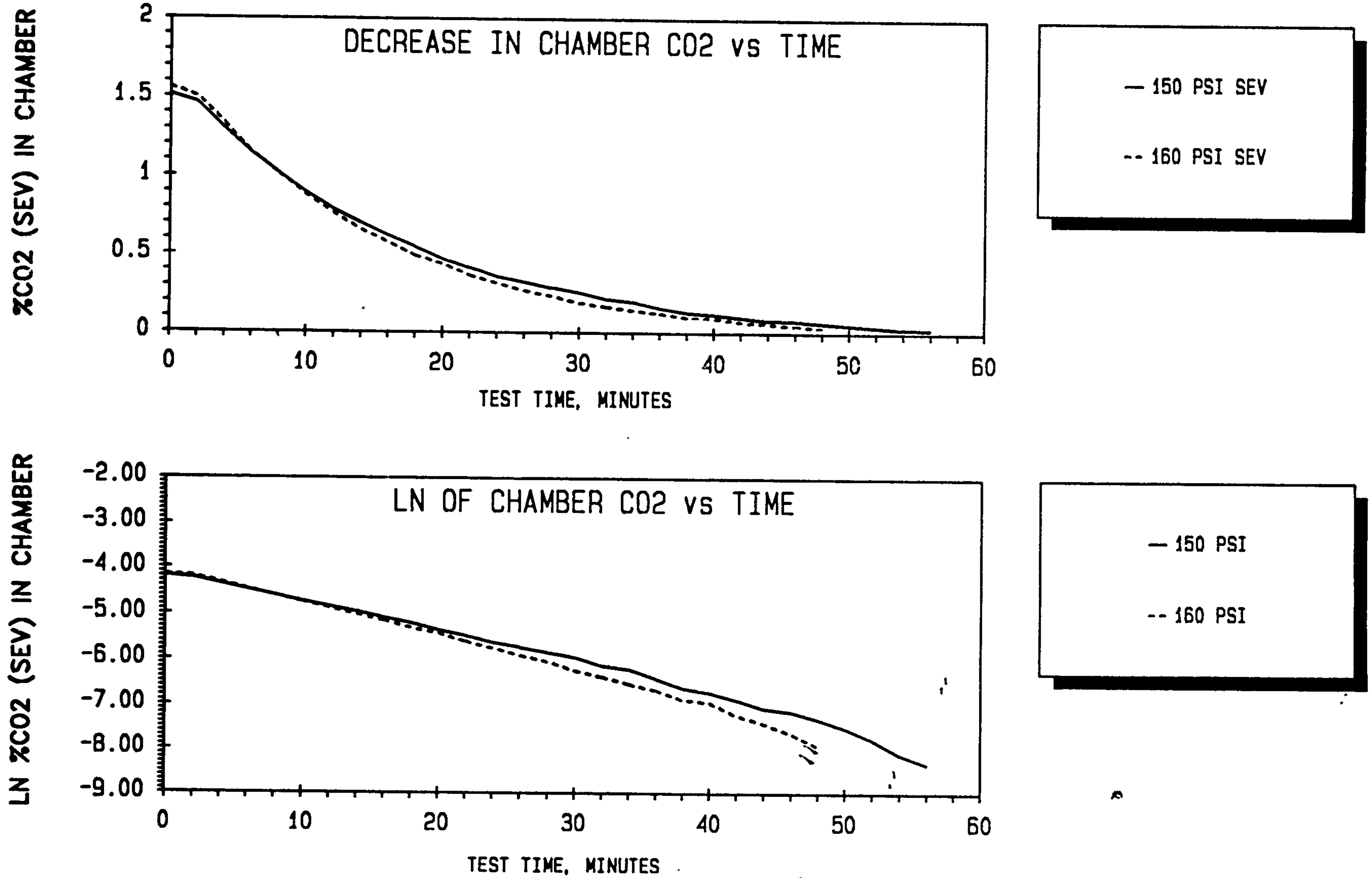


FIGURE 7

CANISTER DURATION STUDY - 30 FSW

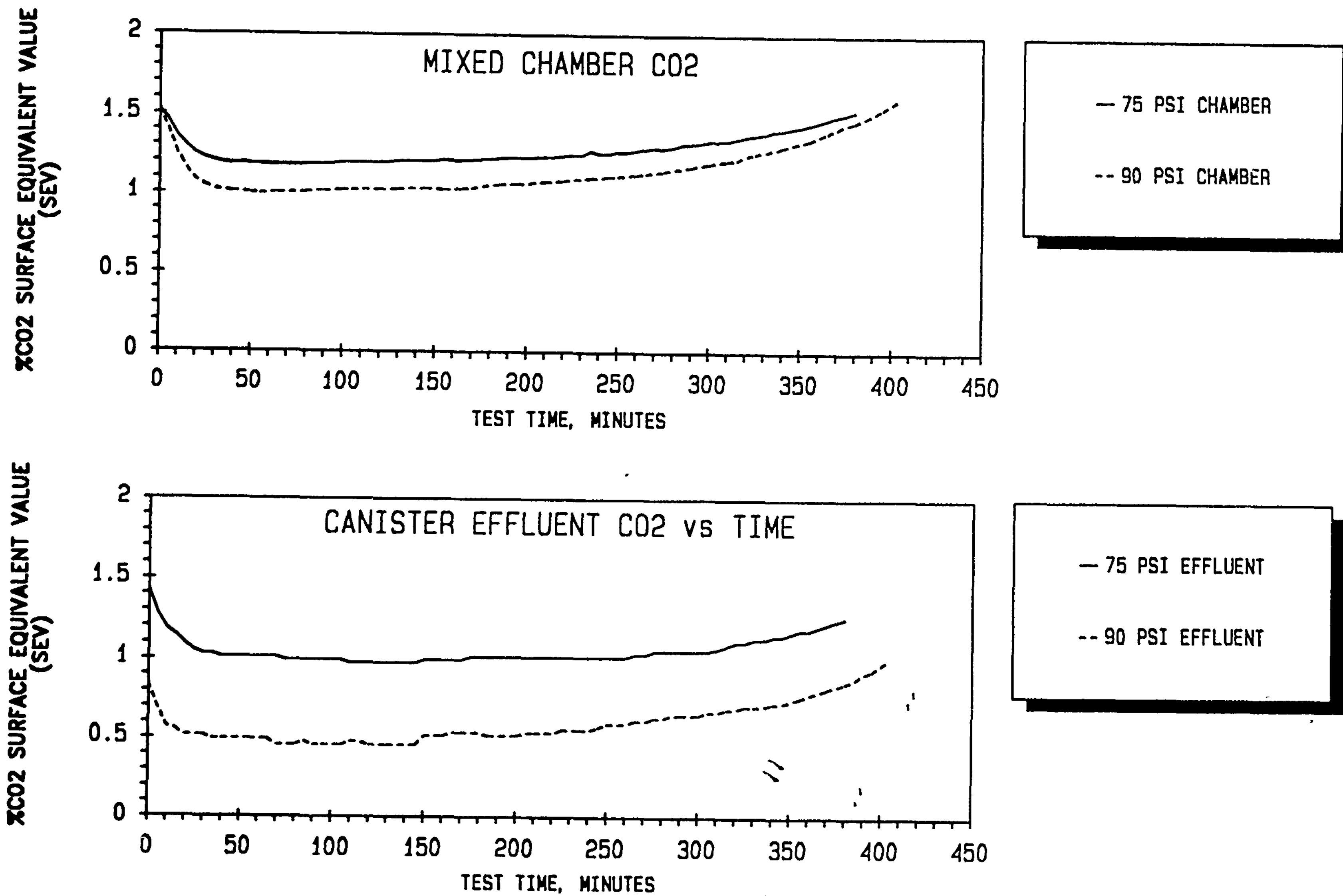
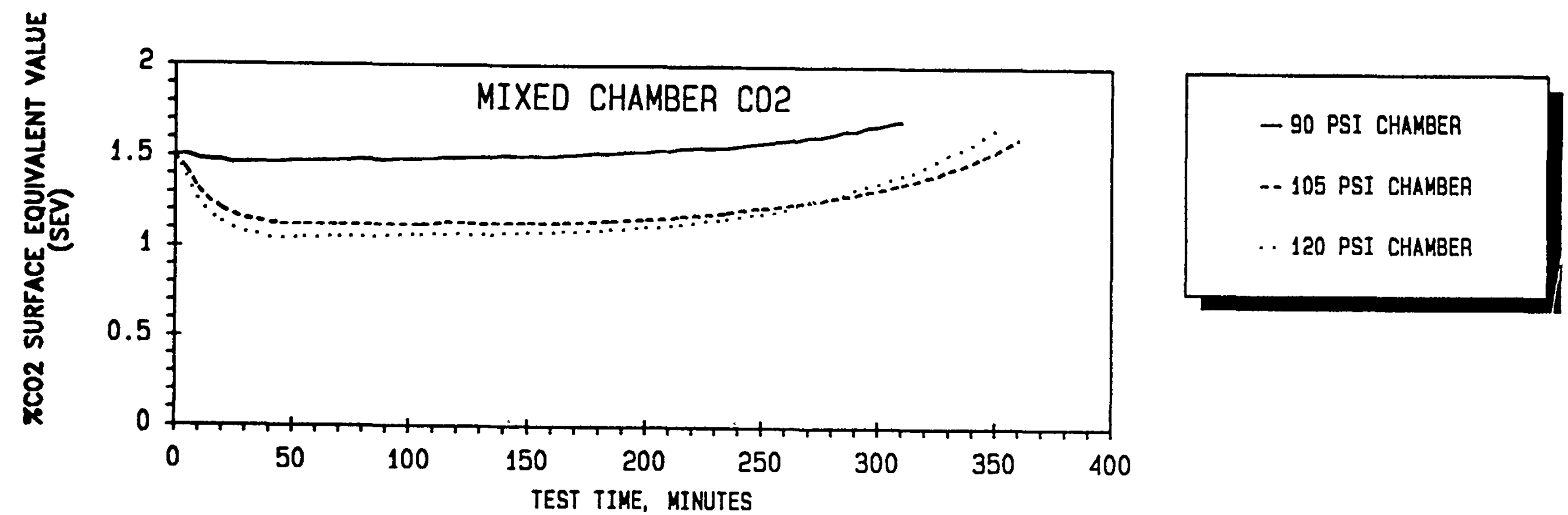


FIGURE 8

CANISTER DURATION STUDY - 60 FSW



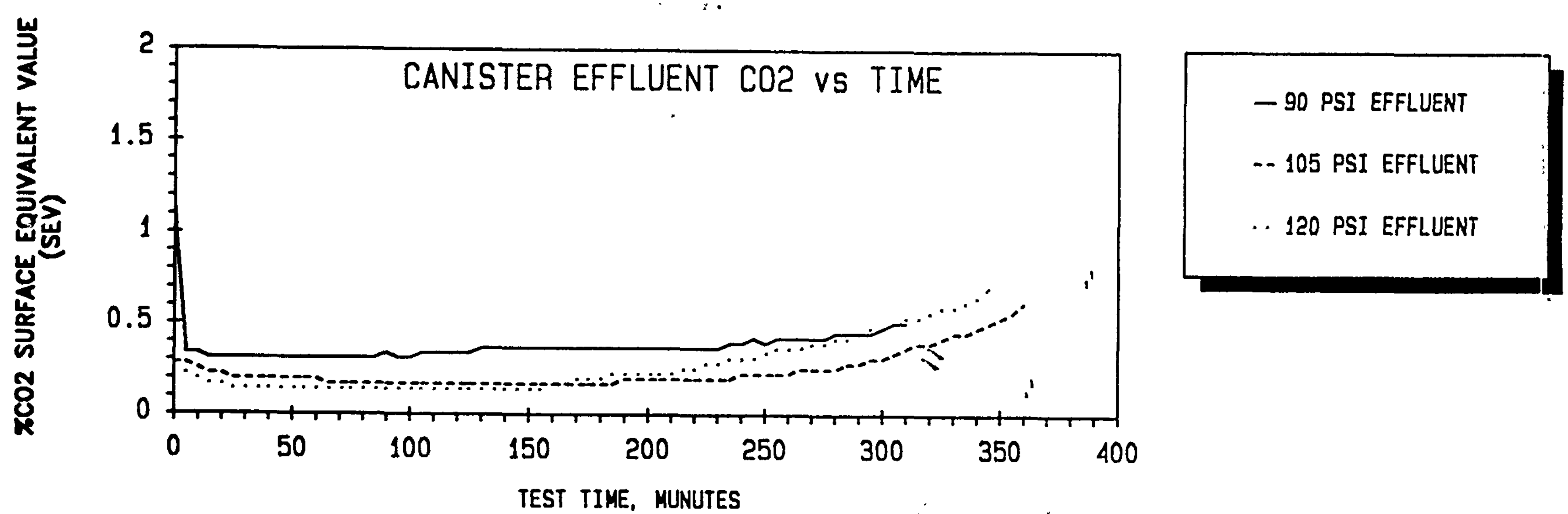


FIGURE 9

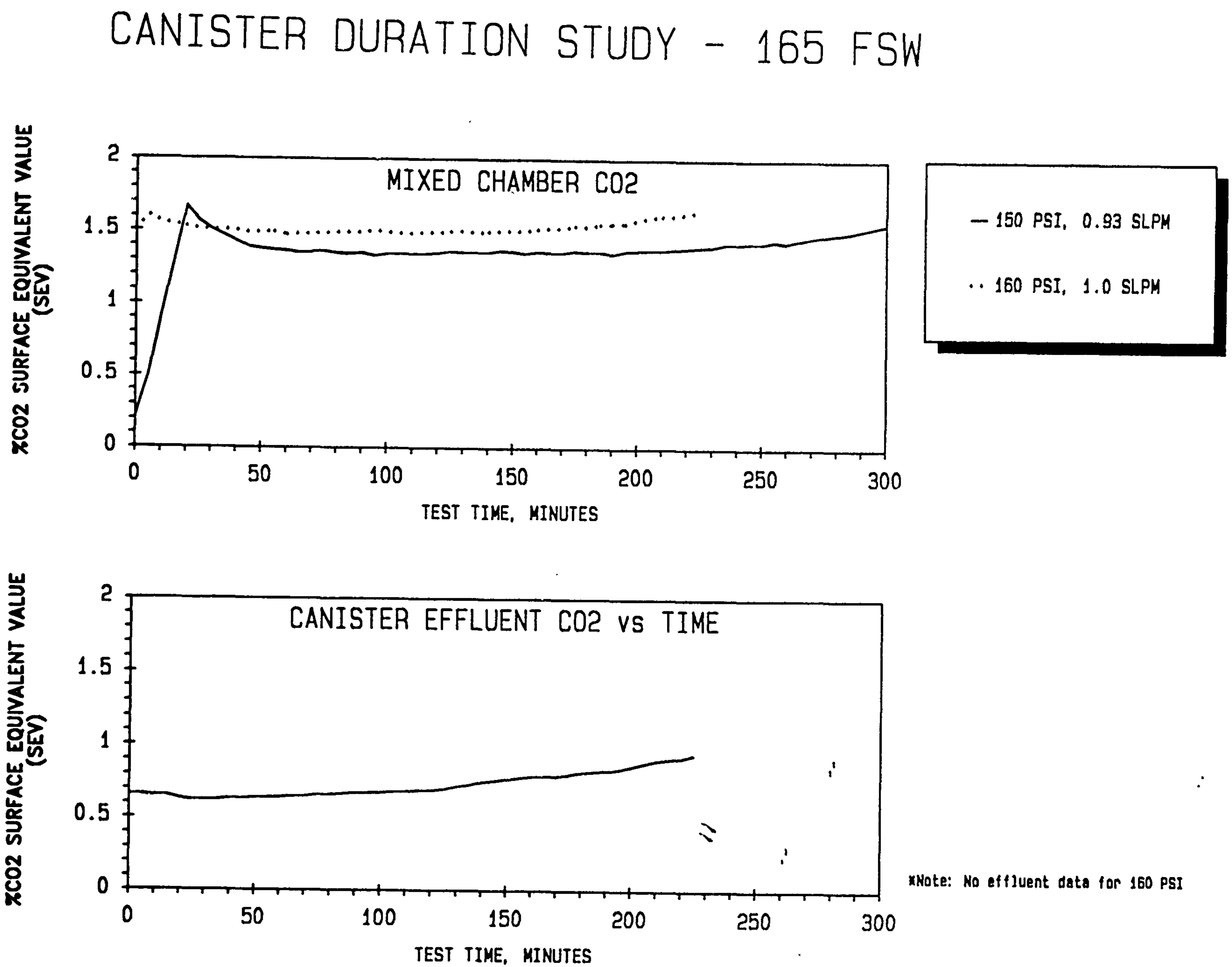

CANISTER DURATION STUDY - 165 FSW
MIXED CHAMBER CO2
%CO2 SURFACE EQUIVALENT VALUE (SEV)
TEST TIME, MINUTES
— 150 PSI, 0.93 SLPM
·· 160 PSI, 1.0 SLPM
CANISTER EFFLUENT CO2 vs TIME
%CO2 SURFACE EQUIVALENT VALUE (SEV)
TEST TIME, MINUTES
*Note: No effluent data for 160 PSI

FIGURE 10

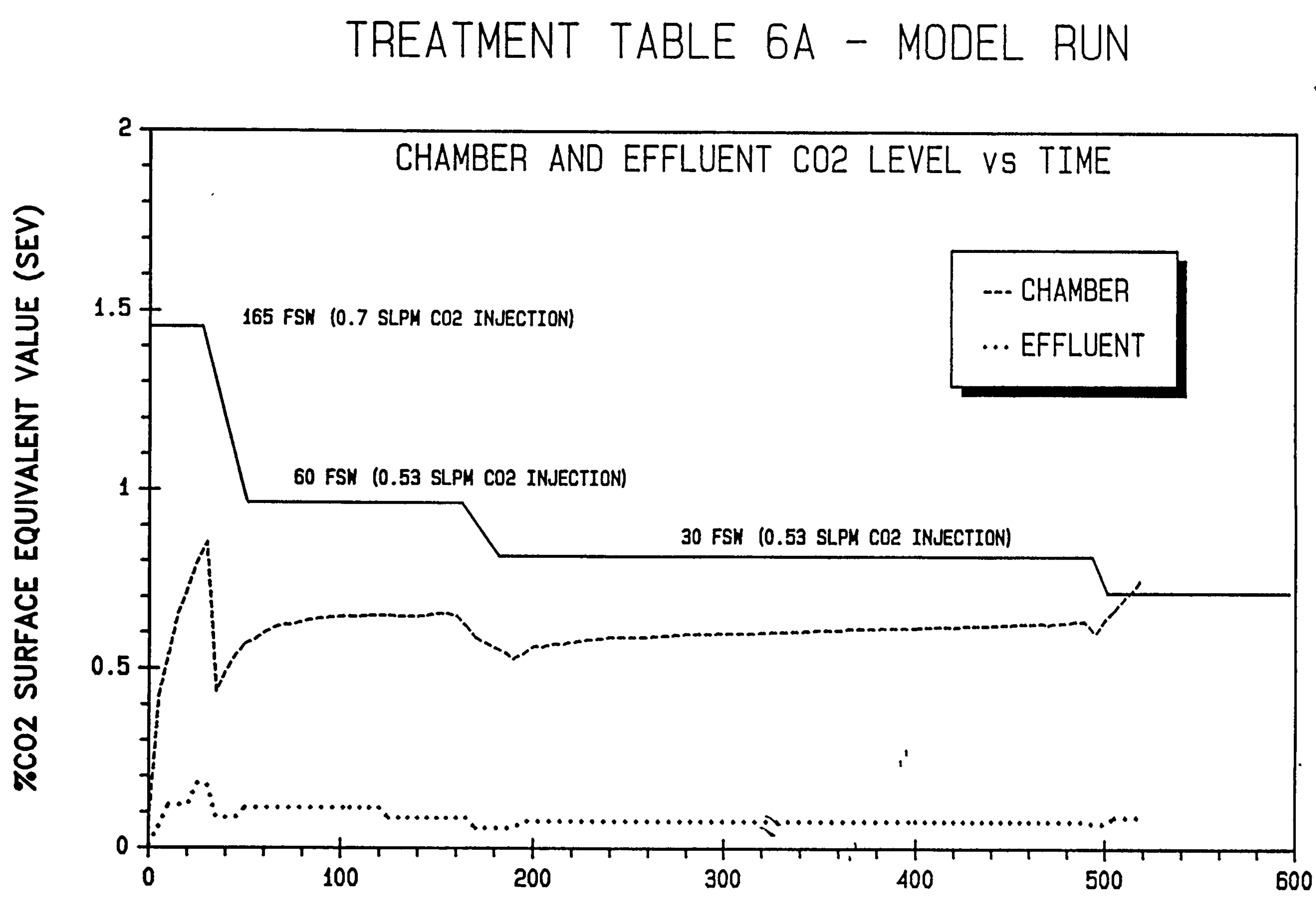

TREATMENT TABLE 6A - MODEL RUN
CHAMBER AND EFFLUENT CO2 LEVEL vs TIME
--- CHAMBER
... EFFLUENT
165 FSW (0.7 SLPM CO2 INJECTION)
60 FSW (0.53 SLPM CO2 INJECTION)
30 FSW (0.53 SLPM CO2 INJECTION)
%CO2 SURFACE EQUIVALENT VALUE (SEV)
TEST TIME, MINUTES
0
0.5
1
1.5
2
0
100
200
300
400
500
600

FIGURE 11

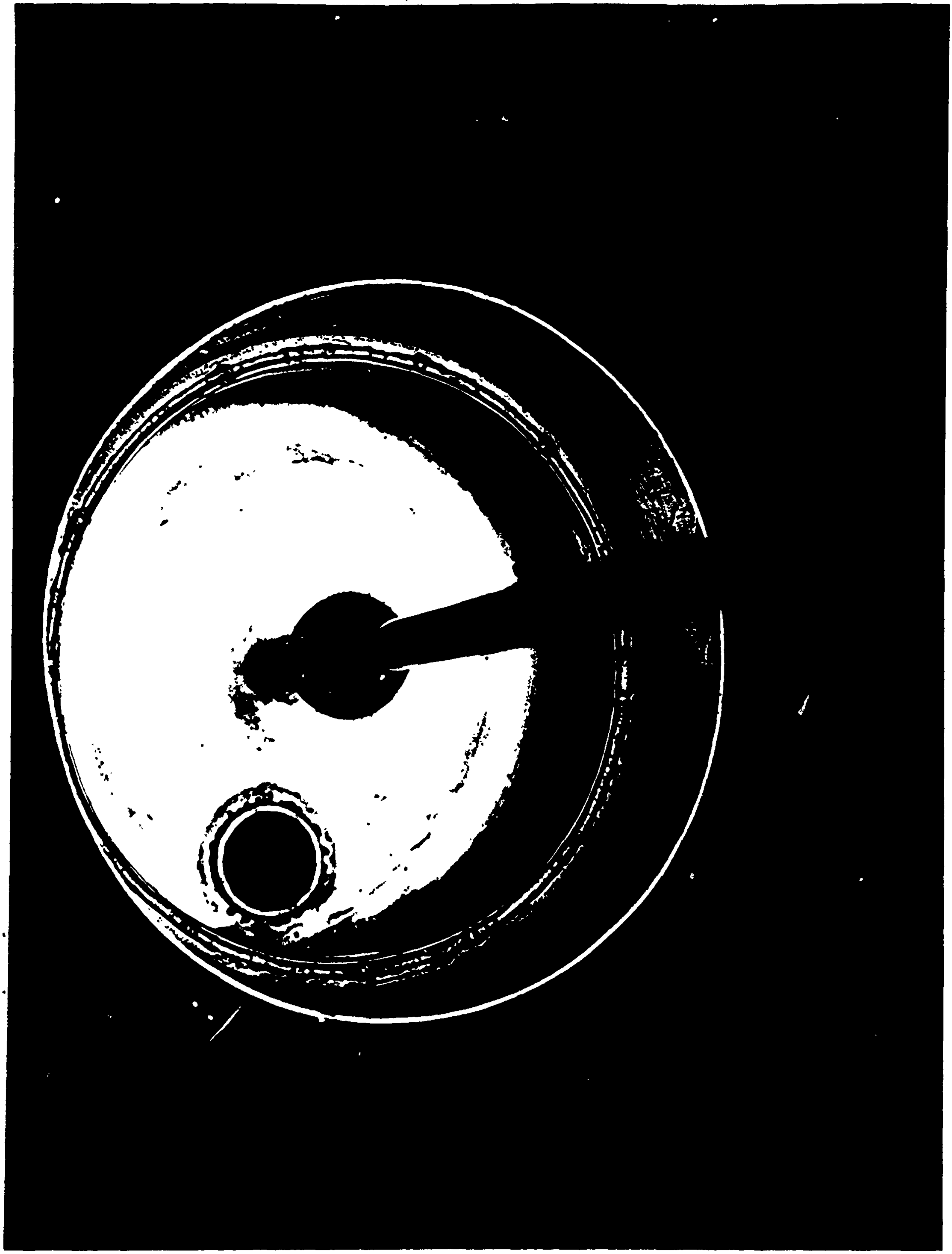


FIGURE 12. PTRCS Scrubber Canister O-Ring Seat